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Historic Load-bearing Structures in Ruins – Fortress Engineering

STRUCTURAL ASSESSMENT OF MASONRY IN RUINOUS STATE

Typology, materials behaviour, non-destructive techniques and consolidation

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Abstract: The typology of masonry castles and fortresses in ruinous state often covers 3-leaf masonry. These walls demonstrate a large complexity, in layout and materials use (brick/stone masonry, mortar types used), in relation to their structural behaviour (different strength and stiffness of the paraments), and in the state of the masonry: heterogeneity or voids, cohesion in between leaves, degradation phenomena. Their failure modes are governed by loss of cohesion in between the different leaves. On site investigation techniques such as endoscopy or geo-electric measurements aim at gathering information of the actual state of the masonry. Grout injection is a possible option for consolidating the load-bearing capacity by means of filling voids and restoring cohesion. Two case studies are treated: the Maegdentoren at Zichem (Tower of Virgins), which is now, after partial collapse in 2006, partially in a ruinous state; and the Castle of Beersel, at which geo-electric measurements have been performed before and after consolidation by means of grout injection.

1. Three leave masonry walls: typology/materials/structural behaviour

Historical masonry structures encountered in Belgium and nowadays in a ruinous state, often date back from Romanesque and Roman periods. The general layout of these walls consists of three-leaf masonry. A relatively thin external leave of 10 to 30 cm at both external sides and a thick infill masonry of 60 cm up till several meters. The large thickness at the bottom decreases stepwise as function of the height. Besides the difference in thickness in the leaves, the material use is different too. The external leave is built up with (regular) brick or stone masonry, the central leave often is a low quality irregular infill masonry. It consists out of smaller pieces or blocks, gravel, sand and a certain amount of (lime) mortar to increase the bond. For example in the case of the “Maagdentoren” or “Tower of the Virgins”, first case study, the tower is a 26 meters high, 15 meters wide ferruginous sandstone tower. The walls have a thickness of 4.2 meters at the base and 1.8 meters at the top, figure 1.

Figure 1. “Maagdentoren” – “Tower of the Virgines” at Zichem (B)

The second case study treats the Castle of Beersel. The bottom part of the external leave is made out of natural stone masonry, with a thickness of 20-30 cm. From on a certain height, the external leave constitutes out of brick masonry with a nominal thickness of 20 cm, figure 2.

Figure 2. “Castle of Beersel (B)

Due to the difference in material use and geometry, a very specific composite load bearing structure is obtained:

- External leave: thin (20-30cm), regular layout, high strength, high stiffness;
- Internal leave: thick (60cm-several meters), irregular layout, low strength, low stiffness.

The actual vertical loading applied on the wall (mainly own weight) is thus mainly transferred to the external leaves due to their higher stiffness, figure 3. Although the external leave is having a regular layout at the external side, often in contact with the internal leave, the surface is not smooth. This enhances, besides the bond in between the external leave and the infill masonry, the hook resistance. That hook resistance increases the overall load bearing capacity and aids in:

- Transferring the loads from the infill masonry towards the stiffer external leaves;
- Increasing the bond in between the infill masonry and the external leaves, and thus;

– Decreasing the slenderness and instability of the thin external leaves subjected to vertical loading.

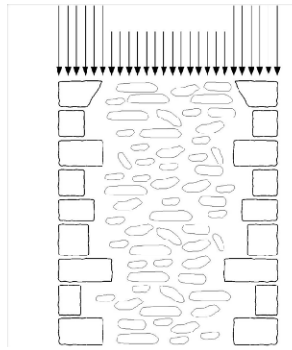


Figure 3. Load bearing behaviour of a sound 3-leaf wall (Van Gemert, 1998)

2. Failure modes

The bond in between the internal leave and the thin external leave is crucial for the overall load bearing capacity (Van Gemert, 1998). Due to degradation phenomena of different nature ruins are exposed to, this bond gets affected. The loss of bond in between the leaves initially mainly affects the load bearing capacity of the external leaves. Without bond, the slenderness of the external leaves increases substantially. Subjected to the vertical loading applied, the external leaves suffer instability, Figure 4.

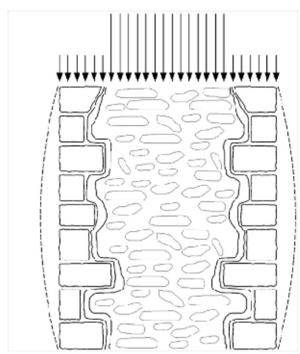


Figure 4. Instability of external leave due to loss of bond in between different leaves (Van Gemert, 1998)

Suffering buckling phenomena, the load bearing capacity of the external leaves is reduced. The loading is no longer transferred from the infill core towards the external leaves as initially. Thus, the infill masonry experiences an increased vertical loading. This increased vertical loading might exceed the overall load bearing capacity of the infill masonry. Perhaps not initially, but as function of time and often due to lack of maintenance, water infiltration, plant growth, creep behaviour, the load bearing capacity of the infill masonry continuously decreases (Verstrynge, 2010). In the final stage a shear band crack failure, similar to soil, is often encountered, Figure 5.

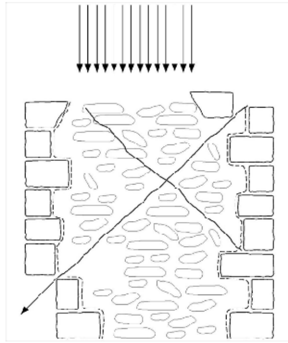


Figure 5. Failure of infill masonry – shear band crack failure (Van Gemert, 1998)

3. On site investigation

On site investigation aims at prematurely recognizing this type of failure: loss of bond in between leaves leading to instability and finally to collapse. For that, visual inspection, endoscopy and geo-electrical measurements are used to provide the crucial information in a diagnosis phase. These techniques do not aim at gathering direct values on the strength of the walls, but at delivering information on the overall state of the wall, signs of malfunctioning, heterogeneity, cracks, voids, etc.

The actual strength of the masonry can be assessed in a subsequent phase, which is beyond the scope of this article, by different means. Although one should keep in mind that for castles, fortresses, towers, the actual average stress level within the masonry hardly ever exceeds 1MPa, which, in case of sound masonry, will not exceed the overall strength of the masonry.

Visual inspection should point on:

- Bulging of walls or external leave, loss of cohesion;
- Degradation phenomena influencing the bond in between the walls (water infiltration, freeze-thaw damage, biological growth, roots of plants in between leaves, leaching out of lime mortar,..);
- Crack patterns, etc..

By means of endoscopy, the internal state of the wall can be visualised. In that, emphasis is put on the (loss of) internal cohesion in between the different leaves, Figure 6. A small borehole is drilled (diameter of 20mm), that allows for the introduction of the endoscopy. (Digital) images or even films of the internal state of the wall are obtained.

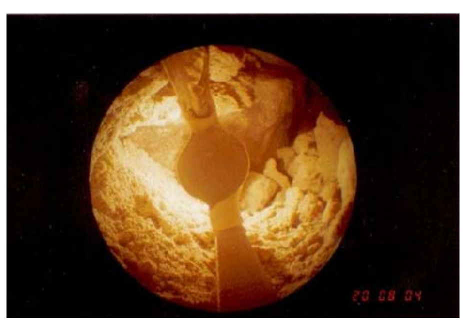


Figure 6. Endoscopy of masonry walls.

Geo-electrical measurements aim at the same information related to the overall state of the masonry. The electric resistivity of the masonry is significantly affected by voids (air with a high electric resistivity). As such a pattern of the electric resistivity can give an overall impression of the heterogeneity of the masonry, and therefore is important information for its load bearing behaviour. In advantage on top of the endoscopic survey, the geo-electric technique is a line scanning technique that results in a line image and in depth information of the wall and thus not only information limited to a single specific point. In addition, the technique can be considered as a non-destructive technique.

Figure 7 shows the necessary measurements for a Wenner-alfa electrode configuration with 20 electrodes. Each of these electrodes, mostly stainless steel nails, can be used to inject current (current electrodes C_1, C_2) or to measure potential (potential electrodes P_1, P_2). Conducting the first row of measurements, a distance "a" (*n = 1*) between C_1P_1, P_1P_2, P_2C_2 is kept constant, leading to 17 (20-3) measurements on this particular row. Raising the electrode distance to "2a" (*n = 2*) gives a bigger influenced zone of the masonry (i.e. more profound penetration of the potential field), resulting in an apparent resistivity value representative for a larger and deeper zone of the masonry. Conventionally, this apparent resistivity value is allocated to a physical point, centrally located between the four electrodes and on a depth equal to the average depth of the influenced zone of the potential field. Note that the second row of measurements (with an electrode distance "2a") has only 14 (20-2×3) measurements. The number of measurements decreases with augmenting electrode spacing (i.e. higher penetration depth). In this way apparent resistivity values are gathered over the depth of the masonry structure and a "pseudo-section", which is the graphical representation of the measured apparent resistivity values, is built (Keersmaekers, 2008).

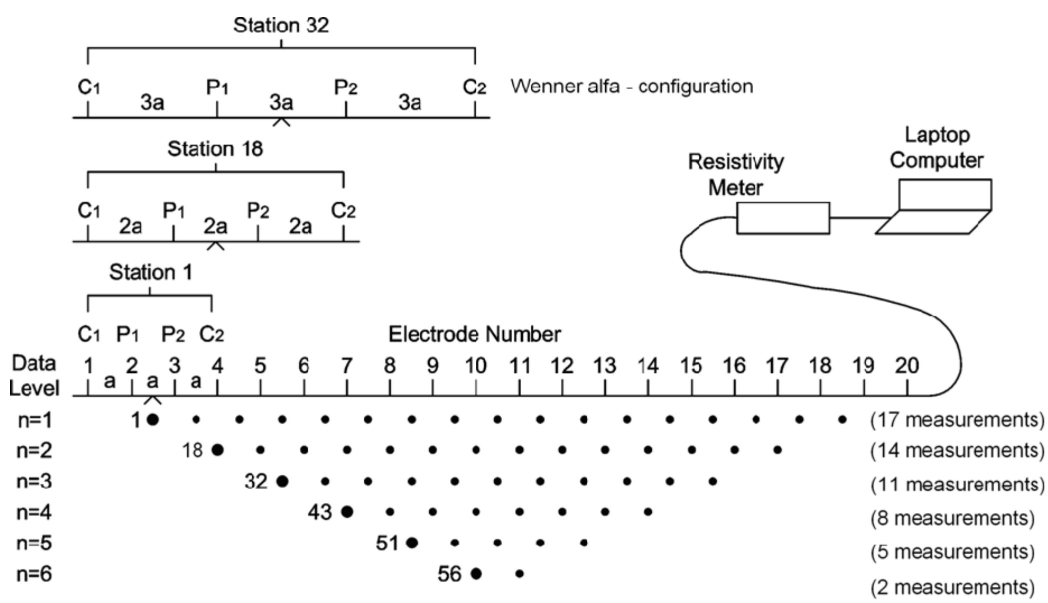


Figure 7. 2D geo-electrical tomography; Wenner-alfa electrode-configuration; subsequent measurements for building a pseudo-section (Van Rickstal et al., 2008)

Unfortunately, the 2D pseudo-section does not enable direct interpretation of the apparent resistivity values. No conclusions about the real resistivity distribution in the substrate (internal structure of the masonry) can be drawn based on apparent resistivity values, Figure 8a. To build the real resistivity distribution it is necessary to numerically invert or transform the pseudo-section values into real resistivity values, Figure 8c. Forward modelling enables the calculation of the apparent resistivity values (pseudo-section), starting from a given resistivity distribution, Figure 8b. The idea is to construct a numerical model with a resistivity distribution whose calculated pseudo-section corresponds with the measured pseudo-section. The section of the wall is therefore numerically divided into blocks or elements, where every element is given a resistivity value. A least square approximation between the calculated and measured pseudo-sections determines how the model parameters (i.e. the resistivity values of the model blocks) must change in the next iteration, resulting in a better correlation between calculated and measured pseudo-sections.

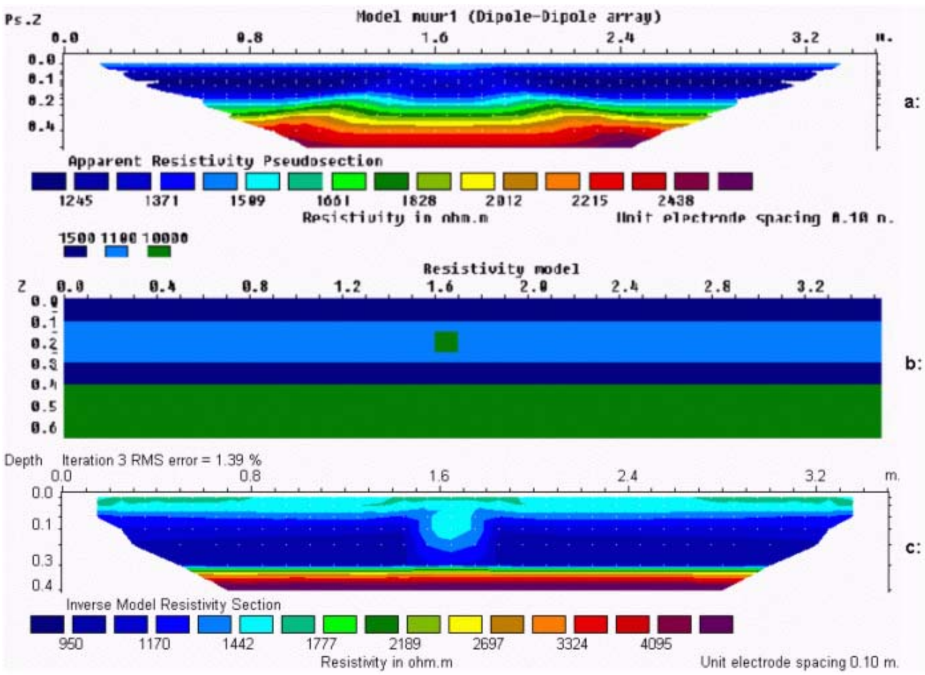


Figure 8. Apparent resistivity – real resistivity – pseudo-section after inversion (Van Rickstal et al., 2008)

In practice, a measuring campaign starts by positioning the electrodes. Stainless steel nails are used for masonry structures. The electrodes are connected to the automatic scanning module which switches the nails as current or potential electrode.

4. Consolidation by means of grout injection

Several techniques have been investigated to re-establish the initial load bearing capacity of these types of walls. Since the initial phase of the failure is initiated by the buckling of the external leaves due to lack of bond, additional restraint can be obtained by means of introducing horizontal anchorages interconnecting the external leave with the internal core masonry, or even interconnection both external leaves. This technique has often been used in the past using metal and later on glass fibre anchorages. As such, the bond is only restored at discrete positions.

An alternative technique consists in re-establishing the bond in between the leaves continuously and in addition, filling voids, cracks and fissures by means of grout injection. As such consolidation focuses on two elements: re-establishing bond within the leaves and increasing the homogeneity of the masonry (Schueremans, 2001; Van Rickstal, 2000, Toumbakari, 2002). It needs to be stressed that the technique not aims at directly increasing the masonry strength by means of a strong and stiff grout. On the contrary, grout injection aims at introducing a material with maximum injectability and compatible with the original material to enhance homogeneity and re-establish bond. As a result, the overall load bearing capacity is again guaranteed, also accounting for maximum material compatibility.

A successful consolidation by means of grout injection therefore depends on numerous factors, such as:

- The grout used for consolidation;
- The pore size distribution of the voids, crack, fissures;
- The execution of the works.

A thorough pre-investigation of the masonry at hand is crucial. At the material scale, there is need for a good knowledge of the original mortar properties. The grout used optimally should be compatible with the original mortar. The compatibility is not only to be reached on the level of mechanical properties (strength and stiffness). Also for example on a chemical and physical (freeze-thaw action) level, compatibility is to be maintained. Therefore, the chemical composition of the original mortar for example is to be known.

Crucial for a successful grout-injection is the injectability of the grout in relation to the proposed chemical composition. A maximum penetration of voids, cracks and fissures is to be obtained to achieve an optimal consolidation. Therefore, optimal rheology by means of low viscosity and high fluidity of the grout are to be looked for. That can easily be checked, also on site, by means of the marsh cone test. The grout should be stable during a sufficiently long period to penetrate within the smaller voids. Therefore, bleeding is to be limited. Water retention is to be carefully looked at. The masonry will suck out the water of the grout. Therefore, the fluidity will decrease and block the grout injection, which has to be prohibited as far as possible.

Also the onsite conditions will play a crucial role for an optimal injection. The mixing procedure is crucial for obtaining a stable grout with high injectability. The number, pattern, diameter and depth of the injection holes drilled of course influence on how the grout can reach the internal voids. The injection pressure is to be kept low, avoiding further damage in the low strength masonry. A continuous loop of the grout flow and a permanent mixing of the grout in the reservoir prohibit segregation of the grout particles. The injection sequence, pressure and injected volumes for each of the injection holes are to be monitored.

The pore size distribution of the voids, present cracks and fissures and their relation with the injectability of the grout and injection procedure, are to be verified within a test injection on beforehand. Initial (qualitative) information on voids is obtained by means of visual inspection, endoscopy and geo-electric measurements.

5. Case study – "Maagendtoren" - "Tower of the Virgins"

The "Maagdentoren" or "Tower of the Virgins" is located at the bank of the Demer river and is a 26 meters high, 15 meters wide ferruginous sandstone tower, figure 9 (Schueremans, 2010). It was constructed around 1380, intended for residentially, military and prestigiously use. A series of necessary repairs were executed in 1863 and 1905. After that, the tower deteriorated for the rest of the century, resulting in a partial collapse of a part of the outside parement in 1995. The biggest catastrophe occurred on June 1st, 2006, when a huge part of the outside wall collapsed. Figure 1 shows an impression of the masonry cross-section and the loss of bond between the leaves. Figure 9 shows the location on the tower where a dipole-dipole electrode configuration was used to perform a geo-electrical tomography (white line). The survey line of the tomography was deliberately partially placed over a visually good looking part of the wall and a bad looking zone. This visually bad looking zone is caused by the demolition of an historic defence platform that was situated there (see Figure 10-left). Figure 10-

right shows the inverted section of the measured survey line, using the dipole-dipole electrode configuration.

The masonry that visually look the worst (zone of the defence platform), show lower resistivities on the tomography (i.e. better cohesion) compared with the adjacent masonry. The results were validated with boreholes, 1 till 3, which overall confirmed the (lack) of cohesion as identified by means of the resistivities measured. Due to the former presence of the defence platform, the extent of deterioration is more limited.

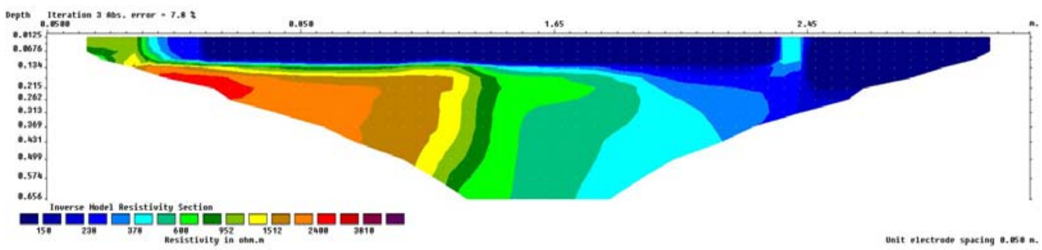
Figure 9. The “Maagdentoren” or “Tower of the Virgins” at Zichem (B) – before and after partial collapse, June 1ste, 2006

Figure 10. Position of the survey line on the tower (left), with Insert: detail with in white the position of the electrodes and in black the position of the historic defence platform, removed in an unknown past, right: position of the electrodes on the wall (white line) and inversion result of dipole-dipole measurements and the location of the boreholes for the endoscopical survey.

6. Case Study – Castle of Beersel

In this case study, the geo-electrical measurement is intended to judge the quality of grout-injections performed as means of consolidation of the masonry. For that reason, the geo-electrical measurements are performed at two stages (Schueremans, 2010). First, a reference measurement is performed before the injection works started. Secondly, the measurement campaign is repeated after consolidation of the masonry using grout injection. Since the geo-electrical measurements give a visual impression of the heterogeneity of the masonry, a comparison before and after injection could enable a qualitative judgement of the consolidation works performed. A total area of about 150 m², figure 11, was monitored before and after grout injection. From that campaign, the areas in which a successful grout injection was obtained could easily be identified, figure 11. In other locations, at which no apparent difference before and after injection could be identified, further investigation was performed, involving adding figures related to the volumes injected in certain areas, and discussion with the contractor performing the injection. As such, without destructive core drillings, the difficulties encountered during the injection were retraced: at specific locations of the masonry the grout penetrability was very limited, at other locations it seemed that the grout flew away towards cavities, etc. As such added value was reached within the overall assessment of the injections performed.

Zone [1] – level 18 pseudo-section before injection



Zone [1] – level 18 pseudo-section after injection

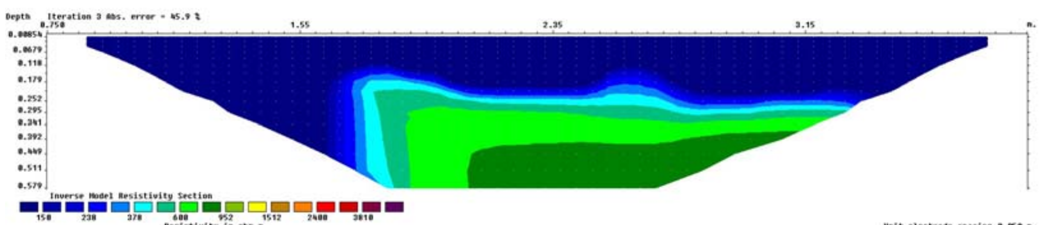


Figure 11: Castle of Beersel – measurement areas and example of one of the pseudo-sections before and after grout injection

After injection a more homogeneous resistivity pattern is obtained with on average lower resistivity values.

7. Conclusion

The load bearing walls of historic castles and fortresses are often made out of three-leaf masonry. Due to the specific load bearing behaviour of the composite wall, the failure mode constitutes from a combination of instability of the external walls and shear of the infill core. Assessing the actual state therefore relies on verifying the cohesion in between the different leaves. That can be performed by visual inspection, endoscopy and geo-electrical measurements as a non-destructive surface scanning technique. Consolidation by means of grout injection aims at re-establishing the bond in between the leaves and increasing the homogeneity within the masonry. Geo-electrical measurements also provide qualitative information related to the effectiveness of the executed consolidation.

Comparison of the geo-electric pseudo-sections before and after consolidation by means of grout injection gives an impression of the increased homogeneity of the masonry. Similar, again endoscopy can be used and of course a limited number of cores can be drilled to actually check the grout injection performed and strength increase obtained.

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